Spectral ray tracing to model the spectrum of a luminaire equipped with an interference filter

Guy Durinck[a], Frédéric B. Leloup[b], Jan Audenaert[c] and Peter Hanselaer[d]

Abstract

In the lighting community ray tracing is a popular tool for the optical design of luminaires. In most cases it suffices to perform ray tracing at one wavelength, typically 555 nm, because the optical properties of most materials used in luminaire design are not strongly dependent on wavelength. In some special purpose luminaires however, optical components are incorporated to modify the spectrum of the light source. A typical application is the illumination of food products in a retail environment. In this paper it is investigated whether spectral ray tracing can be used to predict the angular variation of the spectrum of a luminaire equipped with an interference filter. The input data for the ray tracing simulations are the experimentally determined spectrum of the light source and spectral scattering properties of the materials in the luminaire, and a geometric model of the luminaire. The spectral radiant intensity of the luminaire at a set of emission angles is measured with a goniospectrometer and compared with the spectral radiant intensity found from the ray tracing simulations. A very good agreement is obtained. Additionally, detailed information is gathered through raytracing simulations, on how the light follows different trajectories through the optical system, contributing to the spectral radiant intensity at different emission angles.

Contact information

[a] guy.durinck@kuleuven.be
KU Leuven Technologiecampus Gent, ESAT, Light & Lighting Laboratory
Gebroeders Desmetstraat 1, 9000 Gent, Belgium
[b] frederic.leloup@kuleuven.be
[c] jan.audenaert@kuleuven.be
[d] peter.hanselaer@kuleuven.be

1. Introduction

In the lighting industry Monte Carlo ray tracing software is frequently used to verify the optical performance of a luminaire while still in the design stage. In most cases the ray tracing is performed monochromatic, i.e., for only one wavelength. As the optical properties of most reflector and lens materials used in luminaires are not strongly wavelength dependent the predictions by the simulation software are usually accurate enough to help improve the optical design of the luminaire. However, in some cases the spectrum of the light emitted by the source is, by design, altered by one or more optical components of the luminaire. A typical example of this is the use of colour filters in retail lighting in order to make food products appear more attractive to potential customers. It is well documented that consumer acceptance of a food product strongly depends on the visual appearance of the product, and that the perceived colour of the product is an important visual cue [1]. More in particular, consumers perceive fresh meat and some types of darker coloured fresh fish as more attractive when these are illuminated with a spectrum dominated by red light [2,3]. A computer simulation of such a luminaire needs to take into account the combined influence of the light source, the luminaire optics and often also a colour filter, on the spectrum of the light emitted by the luminaire. Therefore, a ray tracing model of such a device needs to contain the entire visual spectrum of the light source. A luminaire for retail lighting (Flexio from Lunoo) equipped with an SDW-T 100W lamp (Philips) and an interference filter is studied. The interference filter is especially designed to be used in combination with the SDW-T lamp for the illumination of meat products. An interference filter has the advantage that almost no light is lost by absorption in the filter. However, a typical disadvantage of an interference filter is that the spectral transmission depends on the angle at which the light impinges on the filter. This results in the spectrum of the light emitted by the luminaire to be a function of the emission angle. At small emission angles this effect is not apparent to the naked eye but at larger angles a colour shift can be observed. In this paper the spectrum of the light emitted by the luminaire is simulated at several emission angles by means of Monte Carlo ray tracing. The simulated spectra are compared with experimentally determined spectra in the same directions. The simulation takes into account the spectral surface scattering properties of the reflector material, and the angle of incidence dependent spectral reflection and spectral transmission properties of the interference filter. The discharge lamp is modeled with a relatively simple geometric model.

2. Experimental set-up and measurements

2.1 Measurement of optical surface scattering of the reflector material

The reflector material in the luminaire does not primarily reflect in the specular direction but scatters light in a wide angular range around the specular direction. The angular scattering pattern has to be described accurately to enable realistic ray tracing simulations [4,5]. The scattering pattern is mathematically modeled by the Bidirectional Reflectance Distribution Function (BRDF), which is defined as the ratio of the infinitesimal radiance $dL_{e,s}$ of the irradiated sample in a particular viewing direction, to the infinitesimal irradiance $dE_{e,i}$ on the sample by a collimated beam from a particular direction (equation 1). The index *e* is used to indicate that this is a radiometric and not a photometric property and the indices *i* and *s* respectively indicate incident and scattered light. As radiance is emitted or reflected radiant flux per surface area and per solid angle around the viewing direction, and irradiance is incident radiant flux per surface area, the BRDF indicates scatter per solid angle and is expressed in units 1/sr. Because the surface scattering can be wavelength dependent the BRDF is a function of 5 variables: θ_s and ϕ_s are spherical coordinates defining a particular scatter direction relative to the surface normal, θ_i and ϕ_i are spherical coordinates defining the direction of the incident beam, and λ is the wavelength.

$$BRDF(\theta_i,\phi_i,\theta_s,\phi_s,\lambda) = \frac{dL_{e,s}(\theta_i,\phi_i,\theta_s,\phi_s,\lambda)}{dE_{e,i}(\theta_i,\phi_i,\lambda)} \tag{1.1}$$

$$BRDF(\theta_i,\phi_i,\theta_s,\phi_s,\lambda) = \frac{\Phi_{e,s}}{\Phi_{i,s}\Omega_s\,|\cos(\theta_s)|} \tag{1.2}$$

The generic expression for the BRDF (Equation (1.1)) is transformed according to ASTM E1392 [6] into a more practical expression suitable for real world experiments (Equation (1.2)),with $\Phi_{e,s}$ and $\Phi_{e,i}$ the scattered and incident radiant flux, respectively, Ω_s the solid angle subtended by the detector, and θ_s the angle between the surface normal and the scatter direction.

Spectral BRDF measurements of the reflector material are performed in accordance with ASTM E1392 with an experimental set up that was designed and constructed at our laboratory [7]. The solid angle subtended by the device's detector is 0.00062532sr.

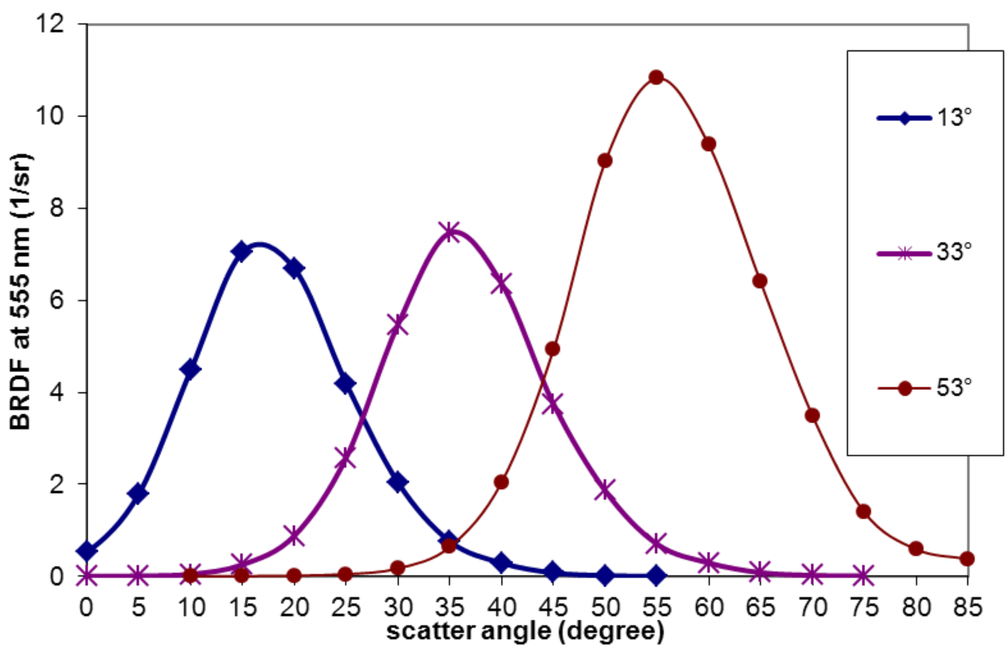

Figure 1: *BRDF of the reflector material as a function of scatter angle at a wavelength of 555 nm at an incident angle of: 13°, 33° and 53°.*

In Figure 1 the experimentally determined BRDF of the reflector material is shown as a function of scatter angle for a number of incidence angles. The data shown are for a wavelength of 555 nm.

The BRDF as a function of wavelength for a particular angle of incidence, i.e., 53°, and a particular scatter angle perpendicular to the surface, is shown in Figure 2. For practically all incidence angles and all scatter angles the BRDF shows the same behaviour as presented: oscillating with a small amplitude around a constant value in the wavelength range 380 nm and 570 nm and oscillating with a small amplitude around a slightly decreasing average value in the range 570 nm and 780 nm. For different incidence and scatter angles, the exact positions of the maxima and minima of the oscillations vary slightly.

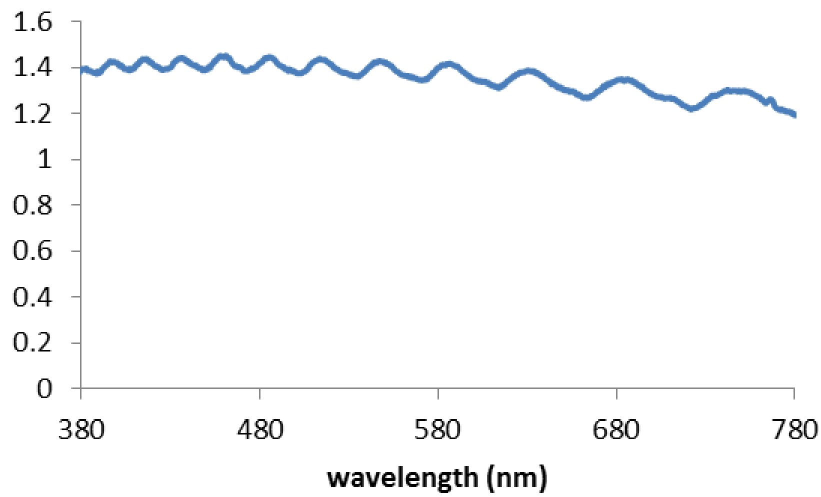

Figure 2: *BRDF (in units 1/sr) of the reflector material as a function of wavelength at an angle of incidence of 53 degree and scatter direction perpendicular to the material surface.*

2.2 Measurement of the transmission and reflection properties of the interference filter

The filter included in the study is an interference filter which consists of a number of thin transparent layers with different indices of refraction. Such a filter uses constructive and destructive interference to transmit light of certain wavelengths at certain incidence angles, and to reflect the same wavelength at other incidence angles. The multilayer is supported on a non-absorbing and non-scattering transparent glass plate. Absorption in the filter is of the order of magnitude of 3%, while scattering is negligible [6]. When placed in the BRDF measurement set up only regular transmission and specular reflection by the filter are observed, which are characterized by the transmission and reflection coefficients, as defined in Equation (1.3) and Equation (1.4).

$$T(\lambda,\theta)=\frac{\Phi_{e,t}}{\Phi_{e,i}} \tag{1.3}$$

$$R(\lambda,\theta)=\frac{\Phi_{e,r}}{\Phi_{e,i}} \tag{1.4}$$

The indices *i*,*t* and *r* respectively refer to the incident, transmitted and reflected flux, the index *e* is used to indicate this is radiant flux (Watt). The transmission and reflection coefficients of the filter are determined as a function of wavelength for a number of incidence angles. In Figure 3, the measured regular transmission coefficient is shown for three incidence angles. Notice that the valley in the transmission coefficient shifts to smaller wavelengths as the incidence angle increases.

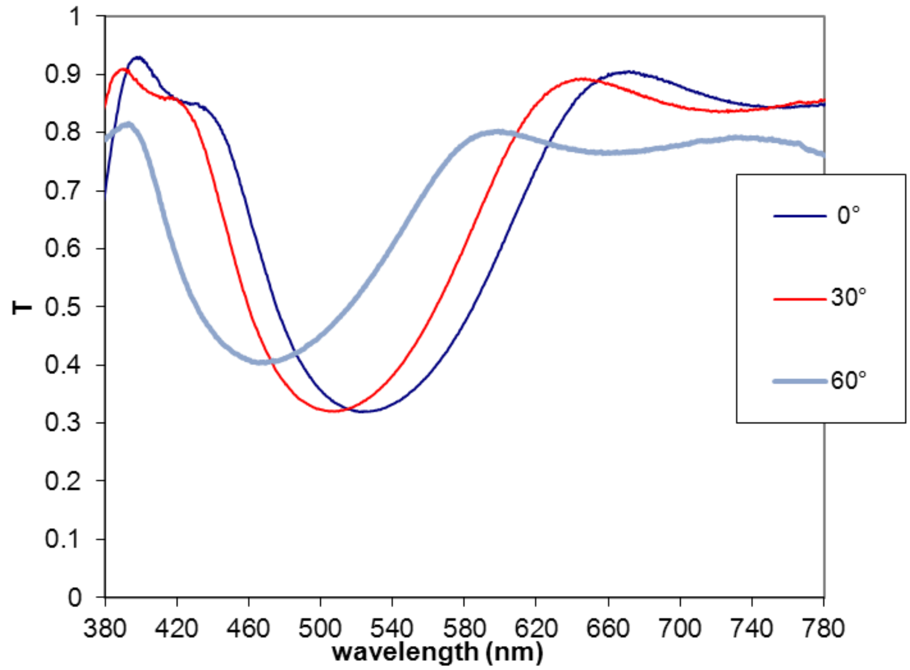

Figure 3: *Transmission coefficient of the interference filter as a function of wavelength for three angles of incidence. Notice that the bottom of the valley in the curve shifts to smaller wavelengths as the angle of incidence increases.*

2.3 Measurement of the output spectrum of the luminaire

The luminaire is mounted in a CIE type 1 [8] goniophotometer which can rotate the luminaire around a horizontal and a vertical axis. Light from the luminaire is captured by a Topcom 100 camera positioned at a distance of 8.72 m from the goniometer, and transferred with an optical fibre to an Oriel Multispec spectrograph equipped with a CCD. Because the detector is in the far field and the entire luminaire is located within the field of view the recorded spectrum is interpreted as the spectral radiant intensity of the luminaire. The spectrum of the naked SDW-T lamp is recorded the same way. The experimentally found spectra will be discussed later together with the simulated spectra.

3. Spectral Monte Carlo ray tracing

All ray tracing is performed with the commercially available software package TracePro® from Lambda Research Corporation. A geometric model of the luminaire is constructed in the software package using CAD-files of the reflector, supplied by the luminaire manufacturer, and a generic model of an SDW-T lamp as found in the TracePro® library. The surface of the cylinder in which the actual gas discharge takes place in a real lamp is considered to be the light source and is modeled as a Lambertian surface source emitter. The BRDF-data for the reflector material and the transmission and reflection properties of the filter are transferred into the appropriate format for the ray tracing software and assigned to the reflector and interference filter in the model. The BRDF-data are somewhat simplified as it is impractical to input the small oscillations that are slightly different for each angle of incidence. Therefore the BRDF is assumed to be constant between 380 nm and 570 nm, and to decrease linearly between 570 nm and 780 nm in such a way that the total integrated scatter (TIS) agrees with the experimentally found value. A disk shaped target with the same dimensions as the entrance pupil (diameter: 3 mm) of the Topcom 100 camera is created in the model and positioned at a distance of 8.72 m from the luminaire. The luminaire model used for ray tracing is shown in Figure 4. Because of the large distance to the

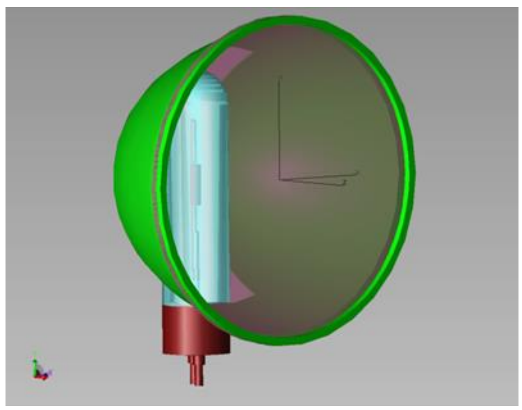

Figure 4: *Model of the luminaire used in the ray tracing simulations.*

source and the small dimensions of the ray tracing target, the probability of a random ray emitted by the source to hit the target is extremely small, making classic source to target ray tracing impractical. Therefore the technique of reverse ray tracing, which is often applied in computer graphics, is applied [9]. In reverse ray tracing rays are traced backwards, from target to source, through the optical system, and a history of all the events (reflection, scattering, etc…) encountered by the rays is logged. When a ray hits the source at a particular angle a flux is assigned to it according to the source properties. Then, taking into account the history of the ray, the flux that would be observed at the target is calculated. This procedure is repeated for 81 wavelengths in the visible range of the electromagnetic spectrum: from 380 nm to 780 nm with 5 nm increments. The relative flux at each wavelength is weighted according to the experimentally determined spectrum of the gas discharge lamp. For each wavelength 1 million rays are launched which, in combination with the relatively complicated geometry and optical properties, results in long computation times; up to 10 hours per wavelength on a dual core 2.31 GHz, 2 GB RAM computer that was available for this simulation. In the IESNA handbook [10] wavelength increments of 2 nm are advised for the spectra of discharge lamps when the spectra are to be used for the calculation of chromaticity. However, this would mean 201 ray tracing runs which proved to be highly impractical because of the long computation times.

4. Results and discussion

Both the experimentally determined spectra and the spectra found by reverse ray tracing are normalized so that the surface area of the spectra from 380 nm to 780 nm equals unity. The simulated spectra can be deconstructed in component spectra for light taking different paths through the optical system. Three component spectra are considered: a spectrum constructed from rays that travel from source to target without being scattered by the reflector (i.e. the direct light contribution), a spectrum constructed from rays that travel from source to target and scatter only once (i.e., there is only one interaction between the light ray and the reflector surface), and a spectrum constructed from rays that scatter more than once. In Figure 5, Figure 6 and Figure 7 the measured and simulated spectra at emission angles of 0 degree, 30 degree and 60 degree respectively, are compared. In all three cases there is a good overall agreement between the experimentally determined spectrum and the spectrum found by spectral ray tracing.

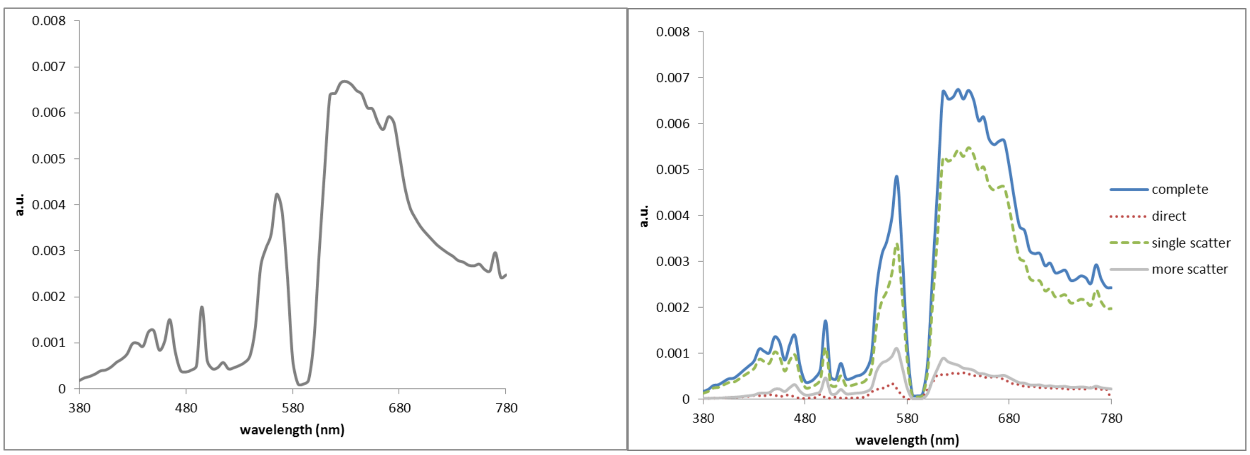

Figure 5: *Experimentally determined spectrum (left) and simulated spectrum (right) of light emitted at emission angle 0° and captured at a distance of 8.72 m from the luminaire. The experimentally determined spectrum and the complete simulated spectrum are normalised to surface area 1, the intensity of the spectrum is in arbitrary units. Notice that the spectrum is dominated by light that reaches the detector after just one scatter (i.e.: one interaction with the reflector).*

The simulations show that the relative contributions to the spectrum by light following different paths changes with the emission angle. At 0 degree the spectrum is dominated by light that has scattered only once at the reflector surface and the contribution of light that has undergone several scattering events is slightly larger than the direct light contribution. At 30 degree emission angle the spectrum is still dominated by light that has interacted with the reflector once but the relative contribution of the direct light is now slightly larger than that of light that has scattered several times. At 60 degree the picture changes dramatically because the observer is now effectively in the shadow cast by the reflector, therefore the direct contribution is zero. The line of sight from source to target is blocked and light from the source can only reach the detector by scattering at least once at the reflector surface. In this case the geometry is such that the spectrum is dominated by light that has undergone multiple scattering events.

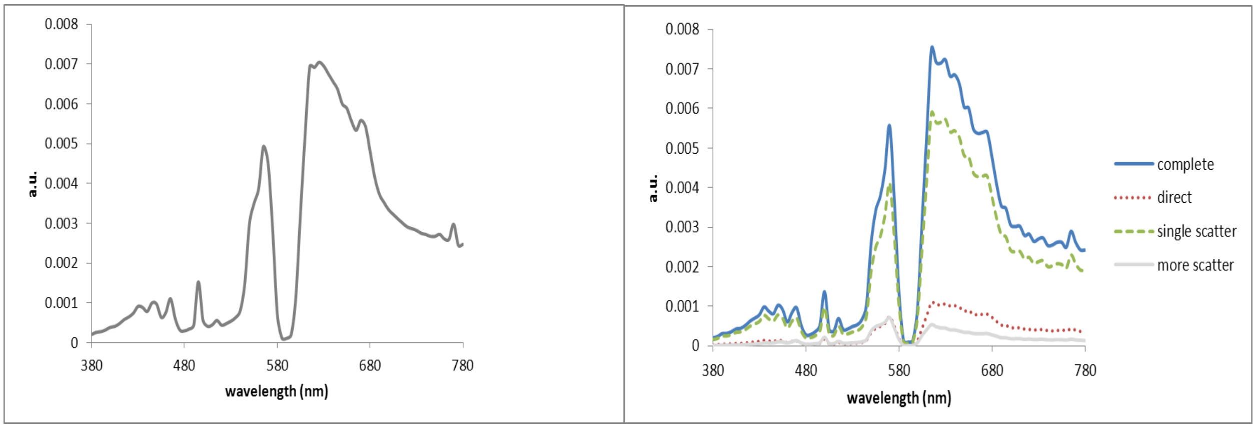

Figure 6: *Experimentally determined spectrum (left) and simulated spectrum (right) of light emitted at emission angle of 30° and captured at a distance of 8.72 m. Notice that the spectrum is dominated by light that reaches the detector after just one scatter and that the direct component now contributes more strongly than the multiple scatter component.*

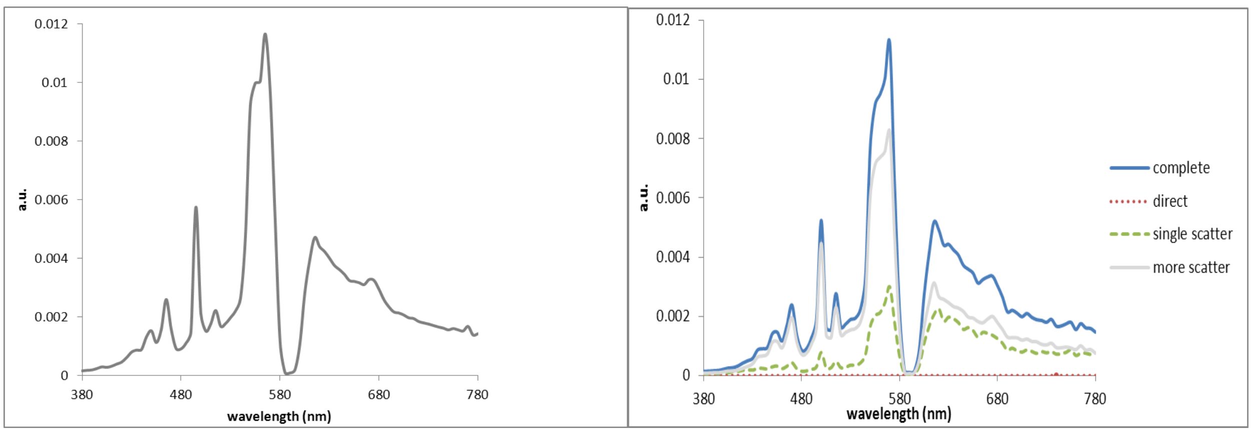

Figure 7: *Experimentally determined spectrum (left) and simulated spectrum (right) of light emitted at an emission angle of 60 degree and captured at a distance of 8.72 m from the luminaire. Notice that the spectrum is dominated by light that reaches the detector after multiple scattering events and that there is no direct contribution from the source. This is because from the point of view of the observer the light source is hidden by the reflector, light from the source can only reach the observer after at least one interaction with the reflector.*

5. Conclusion

Spectral Monte Carlo ray tracing can be used to accurately model the emission angle dependent spectrum of luminaires containing relatively complicated optical components such as interference filters. The computer simulations correspond very well to the measurements and additionally yield interesting information about how the spectrum is composed of light taking different paths through the luminaire and how this composition changes with the emission angle. This type of simulations contribute to a better understanding of unwanted spectral shifts in luminaires and additionally provide a useful tool for the spectral optical design of lighting systems that emulate natural lighting conditions in which the spectrum depends on the viewing direction.

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